FIELD EMITTER ARRAY RF AMPLIFIER DEVELOPMENT PROJECT
ARPA CONTRACT #MDA 972-91-C-0028
PHASE ONE, OPTION 1

SPECIAL TECHNICAL REPORT
17 JAN 94

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MCNC is pleased to report successful demonstration of continuous-wave modulation of field emitter array anode current at 1 GHz. A 1,197-tip array produced a net signal gain of 0.84 dB with DC anode current of 172 μA. Based on test performance data, MCNC has satisfied all of the performance milestones for Phase I of the ARPA Field Emitter Array RF Amplifier Development Project. We understand that competing programs have also met the criteria, but by comparison with the data that has been published, we have exceed their performance in many respects. As better data is collected, it will be promptly reported. Based on these preliminary results, we feel that the device produced at MCNC is the best choice for high-frequency operation.

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INTRODUCTION

MCNC is pleased to report successful demonstration of continuous-wave modulation of field emitter array anode current at 1 GHz. A 1,197-tip array produced a net signal gain of 0.84 dB with DC anode current of 172 μA. Thus we feel that we have satisfied all of the performance milestones for Phase I of the program.

TEST METHOD

Figure 1 shows a schematic diagram of the test equipment used for high-frequency testing. An rf generator is connected to a directional coupler with power meters attached to monitor forward and reflected power. A second directional coupler is attached. The reflected power port of the second coupler is terminated in a 50 Ω load, while the forward power port is fed through a variable attenuator and phase shifter and connected to one input of the Tektronix DSA602A oscilloscope. The forward power signal with attenuation and phase shifting is used as a calibration signal.

The main output of the second coupler is connected to the gate bias tee on the device under test. The gate and anode bias circuits are identical to those used in DC testing as reported earlier. The output of the device is connected through another bias tee to the input of a buffer amplifier. The buffer amplifier output is connected to the other input of the oscilloscope. The buffer is inserted to protect the input of the oscilloscope from the high voltages used on the anode bias, as well as transients generated from the operation of the device under test. The effect of the buffer amplifier, as well as the other components of the test fixture, is removed from the data before the gain is calculated.

Before a measurement is made, the oscilloscope is configured to subtract the calibration signal from the device bleedthrough signal with the emitter off. The variable attenuator and phase shifter are adjusted so that the calibration signal cancels the bleedthrough signal on the oscilloscope display. Since the attenuator is variable in steps of only 1 dB, complete nulling of the bleedthrough signal is not possible. However, calibration of the system in this manner is insensitive to drift in the rf generator. When the field emitter is turned on, a modulated signal appears. This method gives a clearer indication of anode current modulation than the s-parameter measurement used by other programs.

RESULTS

A table comparing MCNC results and test conditions with those reported in the literature by programs at SRI and Raytheon is shown in Table 1. Results from the MIT-Lincoln Labs program are not included, because to our knowledge, they have not reported anode current modulation at 1 GHz. Data for this table was gathered from each program's Phase I summary, as well as data reported at the 1993 International Electron Devices Meeting. Maximum reported and projected performance for MCNC devices is shown in Table 2. This table includes an itemization of the device performance meeting the program goals. Figure 2 shows a timeline listing the progress of MCNC device DC performance. Continuing improvement is expected, and this improvement will be reflected in the rf device performance.

Table 1 shows that comparable net gains at 1 GHz have been achieved by each program. Note, however, that MCNC reports this gain at a much lower anode current than SRI, and with a much smaller array than Raytheon. Further, both rf and DC testing at MCNC are performed with the device operating continuous-wave (CW), that is, at a 100% duty cycle. SRI operates the device in 1-second pulses, in order to prevent damage to the anode. Raytheon also performs rf testing CW, but operates their device at a lower applied gate voltage.

The size of the array used in the tests is also in Table 1. The programs at SRI and Raytheon used the largest arrays that they have been capable of fabricating in their testing. MCNC, on the other hand, uses an array which is relatively small compared to some that have given good results at DC. The total current and transconductance will scale with the number of tips in an array. Larger arrays can also operate at a given anode current level with lower electrical stress on the device. This should result in improved test lifetimes.

Calculated and measured input capacitance is shown for devices produced at MCNC. Raytheon also gives a measured value, while SRI gives an estimate of capacitance neglecting fringing fields in the dielectric. Because of package and test fixture parasitic capacitances, the practical value of the device capacitance is generally quite a bit higher than the calculated value. In practice, this will limit the high-frequency performance of the device. The inherent capacitance of a device with given area and tip spacing is dependent on the specifics of the fabrication process and the materials used. Neither SRI or Raytheon have a process which allows substantial reduction of the device capacitance. The MIT-Lincoln Labs process limits their devices to 300 – 1000 Å of oxide, decreasing as the tip density increases. Eventually, this will produce problems not only with device capacitance, but also with dielectric breakdown. MCNC has the option of increasing column height and oxide thickness to 6 µm or greater, causing a further drop in device capacitance and a proportional increase in f_T.

The devices used for rf testing at MCNC have a 4 µm insulating layer between the substrate and the gate electrode. While DC testing on devices with column heights of 2 µm or less has been ongoing, these devices were not tested at rf because of the anticipated higher device capacitance. Fabrication of the 4 µm devices was completed in early January, and even at this early stage of testing we were able to demonstrate modulation at 1 GHz. As we test more devices we fully expect to observe higher DC emission currents, consistent with the 2 µm column devices, and as a result, higher gain at 1 GHz rf modulation.

The total transconductance for the arrays tested by each program is also shown in Table 1. The value reported by MCNC, 8.7 µS, is calculated from the I-V curve measured during the rf test. The value included for the SRI program, 660 µS, is the only value reported, and applies to a device that was used in another test. The value for Raytheon, 30 µS, is the value used in their equivalent circuit as shown at IEDM. Using these values with the values given for device capacitance allows calculation of f_T for each device.

Measured input impedances for MCNC and Raytheon devices at 1 GHz are comparable, and close to 50 Ω. SRI does not report input impedance, but based on the given value of capacitance, the magnitude should be around 1.6 kΩ, which gives a much larger impedance mismatch at the input of the device.

To verify that the gain was measured accurately at 1 GHz, an identical device was tested using the same test methods, but at lower frequencies (1 – 50 MHz). The resulting data is shown as gain as a function of frequency and anode current in Figure 3. Extrapolating to 1 GHz from this data using the same anode current as in the higher frequency test shows reasonable agreement with the measured data. The gain curves also reinforce the calculated value for f_T for devices produced at MCNC.

SUMMARY

Based on test performance data, MCNC has satisfied all of the performance milestones for Phase I of the ARPA Field Emitter Array RF Amplifier Development Project. We understand that competing programs have also met the criteria, but by comparison with the data that has been published, we have exceed their performance in many respects. As better data is collected, it will be promptly reported. Based on these preliminary results, we feel that the device produced at MCNC is the best choice for high-frequency operation.

FIGURES

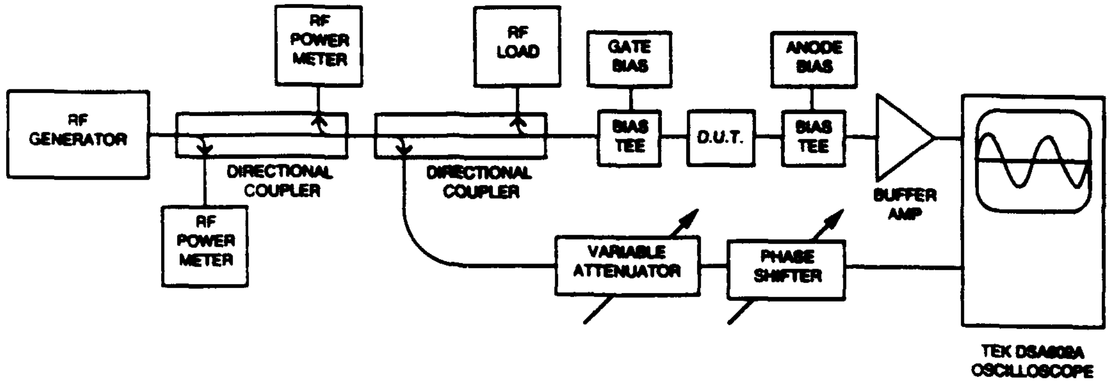

Figure 1: Schematic diagram of the equipment used for high-frequency testing.

DC TEST PERFORMANCE TIMELINE
BY CONTRACT REPORTING PERIOD

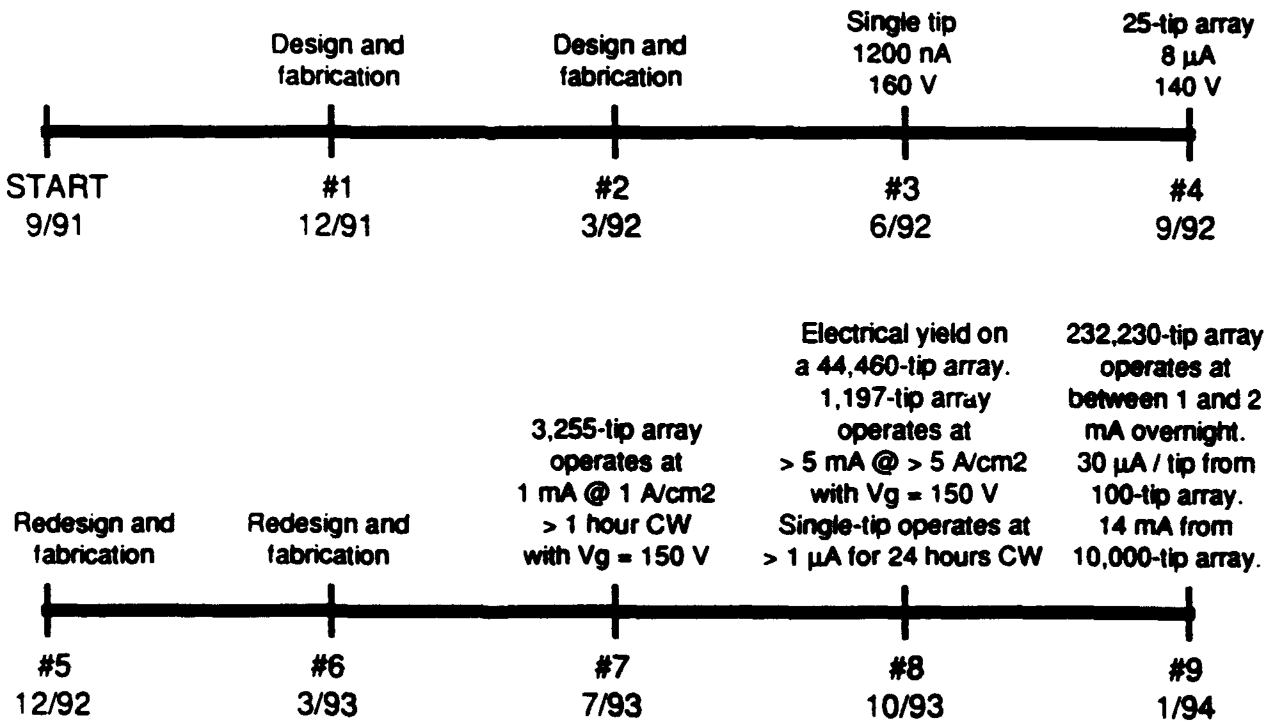

Figure 2: Timeline showing progress of MCNC device DC performance.

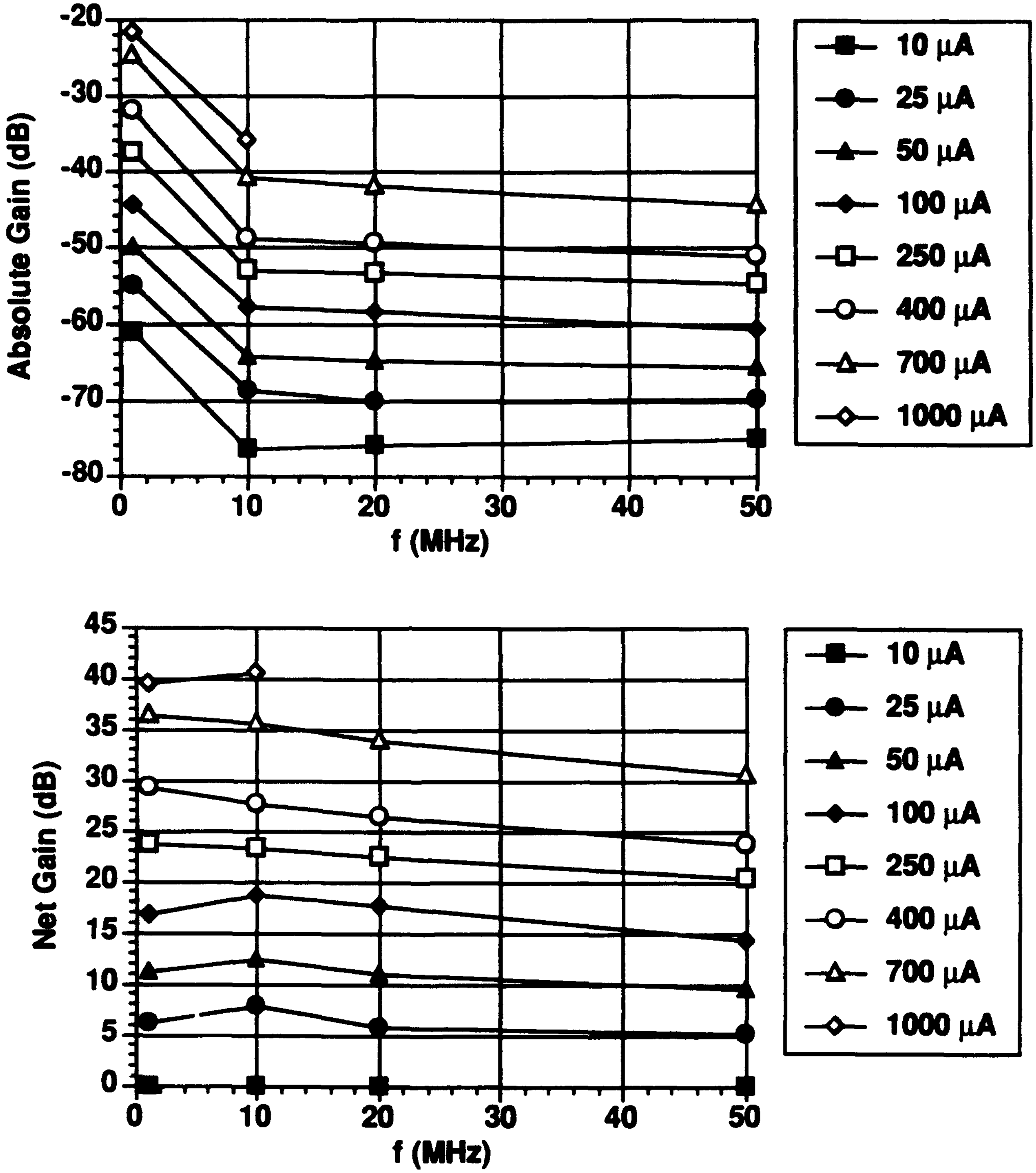

Figure 4: Gain as a function of frequency and anode current at low rf frequencies.

TABLES

	MCNC	SRI	Raytheon
Net Gain at 1 GHz	0.84 dB	0.7 dB	~ 1 dB
Test Mode	CW, rf and DC	1 sec pulse rf, 60 Hz DC	CW rf, 2% duty cycle DC
Anode Current	172 μA	1 mA	150 μA
Gate Voltage	147.4 V	Not Reported	72.3 V
Array Size	1,197	625	26,248
Per-tip Current	144 nA	1.6 μA	5.7 nA
Oxide Thickness	4 μm	1 μm	1 μm
Input Capacitance	1.7 pF (calculated) 4.5 pF (measured)	0.1 pF (estimated)	8 pF (measured)
Total gm	8.7 μS	660 μS	30 μS
f_T	0.308 MHz	1.05 GHz	0.597 MHz
Input Impedance at 1 GHz	20 - j19 Ω	Reported as "high" 1.6 kΩ estimated	6 - j20 Ω

Table 1: Comparison of test conditions and results reported by MCNC and other programs.

	MCNC	SRI	Raytheon
Maximum Anode Current	14 mA	25 mA	70 mA
Maximum Current Density	7 A/cm^2	1000 A/cm^2	8 A/cm^2
Test Lifetime	15 minutes CW rf 24 hours CW DC	> 10 hours of 1 second pulses at 1 GHz > 8700 hours at low duty cycle 60 Hz DC testing	Not Reported
Maximum Per-tip Current	30 μA	100 μA	14 μA
Maximum Per-tip g_m	4.5 μS	5.0 μS	0.8 μS
Typical Emission Efficiency	> 99%	Not Reported	Not Reported
Projected Input Impedance at 10 GHz	20 + j190 Ω	- j160 Ω	6 - j2 Ω
projected net gain at 1 GHz with Ia = 10 mA	15 dB	5 dB	Insufficient information given.

Table 2: Maximum reported and projected performance for MCNC and other program devices.